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Effect of surface roughness on magnetic domain wall thickness, domain size, and coercivity

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We study the effect of surface roughness on magnetic domain wall thickness, domain size, and coercivity of thin magnetic films. We show that the roughness increases (decreases) the domain wall thickness and domain size for Bloch walls (Néel walls). The surface roughness affects the domain wall movement and causes the increase of coercivity for Néel walls. The coercivity due to domain rotation for Bloch walls decreases with the increase of roughness. The domain wall thickness, domain size, and coercivity are each related to the demagnetizing factor, which depends on the roughness and type of wall (Bloch wall or Néel wall). The calculated coercivity versus thickness is compared with experimental data of ultrathin Co films, where the thickness dependent roughness parameters are available. © *2001 American Institute of Physics.* [DOI: 10.1063/1.1331065]

I. INTRODUCTION

Magnetic properties of thin films are influenced by a variety of parameters such as film thickness, crystalline structure, composition, and surface/interface roughness. Specifically, surface/interface roughness influences magnetic properties such as magnetic moments, magnetic anisotropy, coercivity, magnetic domain structure, and motion, etc.[1] Some examples are: the coercivity of chemically etched NiFeCo films (20–100 nm thick) was found to increase with increasing film surface roughness.[2] The coercivity of NiCo-alloy films (~ 2 μm thick) first increases, then decreases, and increases again as the surface roughness increases.[3] Studies in Co films ($\sim$100 nm thick) deposited on plasma etched Si(100) substrates showed that, by increasing surface roughness, the uniaxial anisotropy decreased and disappeared for the roughest films.[4] Moreover, with increasing surface roughness the magnetization reversal changed gradually from magnetization rotation (dominant for smooth films) to domain wall motion (dominant for the roughest films).[4]

The relation of the coercive field H_c for domain wall motion in thin films has been shown to be related by film thickness fluctuations for zig-zag[5] and straight[6] domain walls. Néel,[7] based on the same concept, derived the well known ''4/3'' law for the dependence of coercivity H_c on the film thickness t, $H_c \propto t^{-4/3}$, which is valid under the assumption that the thickness fluctuation dt/dx (with x being the lateral direction along which the wall motion occurs) is constant. However, in many cases (e.g., in NiFe films[6]) such a law appeared to be invalid, in agreement with the fact that a constant dt/dx cannot always be assumed. On the other hand Soohoo[5] fitted a rather wide variety of coercivity data for thicknesses larger than 20 nm under the constraint that dt/dx increases nearly linearly with film thickness. Such an increase of the thickness fluctuations[5] was attributed to roughness changes occurring at short roughness wavelengths.

For ultrathin Co films deposited on rough Cu-buffered Si(111) substrates the coercivity was shown to decay with increasing film thickness t as $t^{-0.4\pm0.1}$ for 12–44 monolayer equivalent (MLE).[8] In epitaxial ultrathin films studies, Co films ranging from 2 to 30 ML deposited on a smooth Cu(001) substrate show that the coercivity increases from about 2 to 7–8 ML, followed by a slight decrease at higher thicknesses.[9] The H_c even oscillates as a function of Co film (4–14 ML) deposited on Cu(001). The oscillation period is 1 ML; this corresponds to the layer-by-layer growth of Co after 2 ML thickness.[10] The H_c for films deposited on roughened substrates are higher. Examples are Co/Cu(001)[9] and Ni/Cu(001).[11]

Defining the relationship between the surface roughness and the coercivity and determining the properties of magnetic domain change with surface roughness are questions of interest when dealing with real films. Recently, we have examined the effect of roughness on the demagnetizing factor of thin magnetic films.[12] In this work we add the energy minimization and extend the study of the demagnetizing factor in Ref. 12 to relate surface roughness with domain property and coercivity. Our treatment is straightforward and can be applied to thin magnetic films. However, we can only find systematic experimental data of both surface roughness and magnetic properties for ultrathin films. When we apply our prediction for thin films to available ultrathin magnetic film data, we obtain a qualitative agreement.

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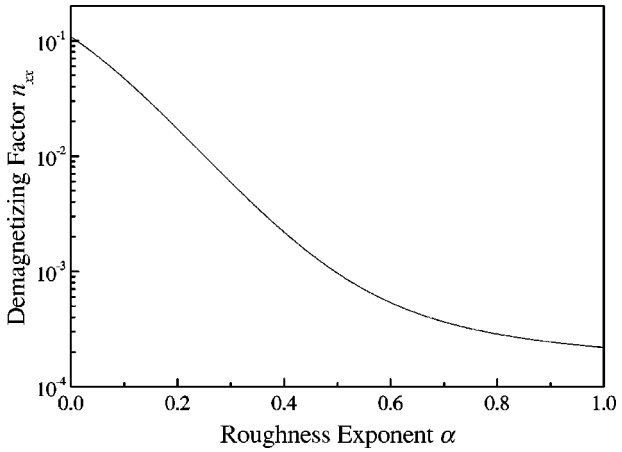

FIG. 1. Demagnetizing factor ratio n_{xx} as a function of roughness exponents α.

II. SURFACE ROUGHNESS MODEL AND DEMAGNETIZING FACTOR

A wide variety of surfaces/interfaces occurring in nature are well described by a kind of roughness associated with self-affine fractal scaling.[13–17] For self-affine fractals the roughness spectrum $\langle|h(\mathbf{k})|^2\rangle$ scales as[18]

$$\langle|h(\mathbf{k})|^2\rangle \propto \begin{cases} k^{-2-2\alpha}, & \text{for } k\xi \gg 1 \\ \text{const}, & \text{for } k\xi \ll 1 \end{cases}, \tag{1}$$

with the roughness exponent $\alpha(0<\alpha<1)$ being a measure of the degree of surface irregularity, such that small values of α characterize more jagged or irregular surfaces at short roughness wavelengths ($<\xi$). Here ξ is the lateral correlation length. The scaling behavior depicted by Eq. (1) can be described by the simple *K*-correlation model:[18]

$$\langle|h(\mathbf{k})|^2\rangle = \frac{F}{(2\pi)^4}\frac{w^2\xi^2}{(1+ak^2\xi^2)^{1+\alpha}}, \tag{2}$$

where F is the surface area we consider, w is the root-mean-square (rms) roughness, and $a=(1/2\alpha)[1-(1+aQ_c^2\xi^2)^{-\alpha}]$, with Q_c being the upper spatial frequency cutoff. The rms local slope defined as $\rho_{\text{rms}}=\sqrt{\langle|\nabla h|^2\rangle}$ can be expressed as

$$\rho_{\text{rms}} = \left(\frac{(2\pi)^4}{F}\int k^2\langle|h(\mathbf{k})|^2\rangle d\mathbf{k}\right)^{1/2}. \tag{3}$$

The demagnetizing factors satisfy

$$N_{xx}+N_{yy}+N_{zz}=1. \tag{4}$$

Under the small slope assumption $\rho_{\text{rms}}\ll 1$ and for an isotropic surface, $N_{xx}=N_{yy}$, we have an in-plane demagnetizing factor:[12]

$$n_{xx}=\frac{N_{xx}}{N_{zz}^0}\approx\frac{(2\pi)^4}{2tF}\int\frac{k_x^2}{k}\langle|h(\mathbf{k})|^2\rangle d\mathbf{k}. \tag{5}$$

Here N_{zz}^0 is the demagnetizing factor for a smooth film in the z direction and t is the film thickness. n_{xx} is proportional to w^2, while its relationship with ξ and α is more complicated as seen in Eqs. (4) and (5), and in Ref. 12. Figure 1 shows a typical plot of n_{xx} as a function of α. n_{xx} decreases as α increases (i.e., as the surface roughness becomes less wiggly).

III. DOMAIN WALL THICKNESS

The surface energy σ_w for a domain wall can be written as[19–21]

$$\sigma_w=\sigma_{ex}+\sigma_{an}+\sigma_{\text{mag}}, \tag{6}$$

where σ_{ex} is the exchange energy, σ_{an} is the anisotropy energy, and σ_{mag} is the magnetostatic energy. In general, for 180° domain, the exchange energy σ_{ex} can be expressed as

$$\sigma_{ex}=\frac{A_{ex}\pi^2}{D}, \tag{7}$$

where A_{ex} is the exchange constant defined as $A_{ex}=JS^2/a_0$, J is the exchange integral, S is the spin, and a_0 is the atomic length scale. D is the thickness of the domain wall.

The anisotropy energy σ_{an} can be written as

$$\sigma_{an}=\frac{K_1D}{2}, \tag{8}$$

where the in-plane anisotropy constant $K_1=K_v+2K_s/t$, K_v is the in-plane volume anisotropy constant, K_s is the surface anisotropy constant.[22] (Here we only consider the uniaxial anisotropy contribution.)

The magnetostatic energy σ_{mag} is

$$\sigma_{\text{mag}}=\pi NDM_s^2, \tag{9}$$

where N is the demagnetizing factor for the magnetic domain wall and M_s is the saturation magnetization.

Therefore, Eq. (6) can be rewritten as

$$\sigma_w=\frac{A_{ex}\pi^2}{D}+\frac{K_1D}{2}+\pi NDM_s^2. \tag{10}$$

The minimization of surface energy for the domain wall $\partial\sigma_w/\partial D$ requires that

$$-\frac{A_{ex}\pi^2}{D^2}+\frac{K_1}{2}+\pi NM_s^2+\pi DM_s^2\frac{\partial N}{\partial D}=0. \tag{11}$$

There are two kinds of magnetic domain walls: Bloch wall for thick films in which the magnetization rotates out of the film plane when crossing the wall and Néel wall for thin films in which the magnetization rotates within the film plane when crossing the wall. For both Bloch and Néel walls, σ_{ex} and σ_{an} are the same. However, the magnetostatic energy σ_{mag} is different due to the difference in the demagnetizing factor N. For a Bloch wall with a perfectly flat surface:

$$N_{\text{Bloch}}^0=\frac{D}{t+D}. \tag{12}$$

For a Néel wall with a perfectly flat surface

$$N_{\text{Néel}}^0=\frac{t}{t+D}. \tag{13}$$

These are well-known results.[19–21]

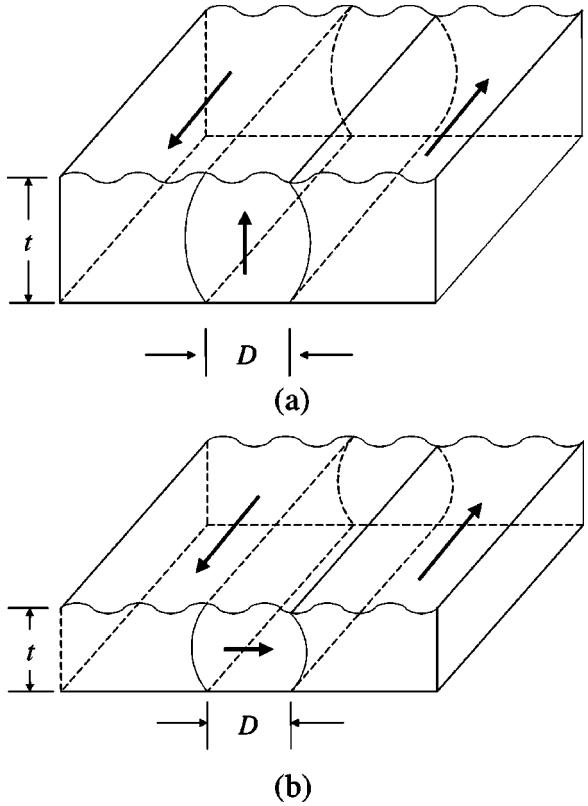

FIG. 2. (a) Bloch wall, and (b) the Néel wall. D and t are wall thickness and film thickness, respectively.

Now we consider the surface of a magnetic film to be rough. For a Bloch wall, as shown in Fig. 2(a), the surface roughness will decrease the demagnetizing factor perpendicular to the film surface, according to Eq. (4):

$$N_{\text{Bloch}} \approx N^0_{\text{Bloch}}(1-2n_{xx}). \tag{14}$$

Here n_{xx} is the ratio N_{xx}/N^0_{zz}, which is greater than zero for a rough surface. However, for a Néel wall, as shown in Fig. 2(b) where the magnetization, the surface roughness will increase the demagnetizing factor parallel to the film surface:

$$N_{\text{Néel}} \approx N^0_{\text{Néel}}(1+n_{xx}). \tag{15}$$

Now if we assume n_{xx} is not a function of domain wall thickness D (which means $D \gg \xi$), we can estimate the effect of roughness on the D. For a Bloch wall, in the bulk limit $t \gg D$, the magnetostatic energy term σ_{mag} can be neglected:[20,21]

$$D \approx \sqrt{2}\pi(A_{ex}/K_1)^{1/2}, \tag{16}$$

i.e., the domain wall thickness almost does not change with surface roughness. However, if $K_1 \ll 2\pi M_s^2$, the anisotropy energy σ_{an} can be neglected, and

$$D \approx \pi\left(\frac{A_{ex}}{\pi(1-2n_{xx})M_s^2}\right)^{1/2} \approx \frac{\sqrt{\pi A_{ex}}}{M_s}(1+n_{xx}), \tag{17}$$

i.e., the domain wall thickness will increase. The surface energy of the domain wall becomes

$$\sigma_w = \pi M_s\sqrt{4\pi A_{ex}(1-2n_{xx})} \approx 2\pi^{3/2}A_{ex}^{1/2}M_s(1-n_{xx}), \tag{18}$$

i.e., the surface energy of the domain wall will decrease.

For a Néel wall, if $t \gg D$, Eq. (11) gives

$$D \approx \pi\left(\frac{A_{ex}}{\pi(1+n_{xx})M_s^2}\right)^{1/2} \approx \frac{\sqrt{\pi A_{ex}}}{M_s}\left(1-\frac{1}{2}n_{xx}\right), \tag{19}$$

and

$$\sigma_w = \pi M_s\sqrt{4\pi A_{ex}(1+n_{xx})} \approx 2\pi^{3/2}A_{ex}^{1/2}M_s\left(1+\frac{1}{2}n_{xx}\right). \tag{20}$$

Thus the Néel wall thickness decreases with the roughness but the wall energy increases. We notice that in this case D cannot always decrease according to Eq. (19), because as D approaches ξ, n_{xx} also becomes D dependent.

IV. DOMAIN SIZE

Next we consider the effect of surface roughness on the domain size for a closure domain. The domain energy E_d can be written as a sum of wall energy E_w, anisotropy energy E_{an}, and magnetostatic energy E_{mag}:[21]

$$E_d = E_w + E_{an} + E_{\text{mag}} = \frac{\sigma_w[t+(\sqrt{8}-1)L]}{L} + \frac{K_1 L}{2} + \pi N L M_s^2, \tag{21}$$

where L is the domain size. Usually, for $L \gg \xi$, N is independent on L. Thus the energy minimization process gives the size of the domain wall:

$$L = \left(\frac{2\sigma_w t}{K_1 + \pi N M_s^2}\right)^{1/2}. \tag{22}$$

If we assume the effect of roughness on the surface energy σ_w of a domain wall is small, then σ_w is almost a constant. Therefore, for a Bloch wall, we have

$$L_{\text{Bloch}} = \left(\frac{2\sigma_w t}{K_1 + \pi(1-2n_{xx})M_s^2}\right)^{1/2}, \tag{23}$$

i.e., the increase of surface roughness will increase the size of the Bloch domain. However, for a Néel wall

$$L_{\text{Néel}} = \left(\frac{2\sigma_w t}{K_1 + \pi n_{xx} M_s^2}\right)^{1/2}, \tag{24}$$

i.e., the increase of surface roughness will decrease the size of Néel domain.

V. COERCIVITY

A. Wall movement

The coercivity of a thin magnetic film caused by domain wall movement can be written as[6,20]

$$H_c^{\text{mov}} = \frac{1}{2M_s}\left(\frac{\partial\sigma_w}{\partial t}\frac{dh}{dx} + \frac{\sigma_w}{t}\frac{dh}{dx} + \frac{\sigma_w}{l}\frac{dl}{dx}\right), \tag{25}$$

where h is the surface height and l is the length of the wall. According to Soohoo[5] one can assume that the length of wall l remains unchanged during the wall movement, we have

$$H_c^{\mathrm{mov}}=\frac{1}{2M_s}\left(\frac{\partial\sigma_w}{\partial t}+\frac{\sigma_w}{t}\right)\frac{dh}{dx}. \tag{26}$$

From a statistical point of view, for a rough surface, we replace (dh/dx) by rms local slope ρ_{rms}. The rms local slope is unitless and yields a measure of the average local surface slope. Thus, Eq. (26) becomes

$$H_c^{\mathrm{mov}}=\frac{1}{2M_s}\left(\frac{\partial\sigma_w}{\partial t}+\frac{\sigma_w}{t}\right)\rho_{\mathrm{rms}}. \tag{27}$$

Therefore, we learn that the coercivity is closely related to surface roughness. According to Eq. (10), for a Néel wall, we have

$$\sigma_w=\frac{A_{ex}\pi^2}{D}+\left(\frac{K_v}{2}+\frac{K_s}{t}\right)D+\frac{tD}{t+D}\pi M_s^2. \tag{28}$$

Therefore, the coercivity caused by domain wall movement can be written explicitly as

$$H_c^{\mathrm{mov}}=\frac{1}{2M_s}\left(\frac{\pi D^2M_s^2}{(t+D)^2}+\frac{2\pi DtM_s}{t+D}\frac{\partial M_s}{\partial t}+\frac{A_{ex}\pi^2}{Dt}+\frac{K_vD}{2t}+\frac{\pi DM_s^2}{t+D}\right)\rho_{\mathrm{rms}}. \tag{29}$$

Here we consider the possibility of the thickness dependent M_s. In general, for an ultrathin film, the saturation magnetization M_s depends on the film thickness. According to Glass and Klein,[23] for a face-centered cubic (fcc) film:

$$\frac{M_s(t)}{M_s^0}=1-\frac{1}{16\pi S^2G_3}\frac{kT}{J}\sum_{\lambda_3=0}^{G_3}(1+\cos k_3)^{-1}\times[\ln(1-e^{-B})-\ln(1-e^{-A})], \tag{30}$$

where M_s^0 is the bulk saturation magnetization, G_i is the number of cubic cells in the ith direction of the crystal, G is a large number ($\sim 10^7$ or more), and

$$A=\frac{16JS}{kT}[(1+\pi^2/4G^2)-(1-\pi^2/4G^2)\cos k_3],$$

$$B=\frac{16JS}{kT}[(1+\pi/4)-(1-\pi/4)\cos k_3],$$

$$k_3=\frac{2\pi\lambda_3}{G_3}.$$

In fact, $G_3=t/a_0$, where a_0 is the lattice constant and λ_3 is an index. Note that in comparing with experiments, it is not the local spin S that is determined by the effective magnetic moments per atom (m) and g values. Thus, in Eq. (30) the spin S should be effectively replaced by $S=m/gm_B$ with m_B the Bohr magneton. At any rate, the coercivity has a complicated relationship as a function of the film thickness t.

For a thin film, when the saturation magnetization M_s becomes a constant, Eq. (29) can be reduced as

$$H_c^{\mathrm{mov}}=\frac{1}{2M_s}\left(\frac{A_{ex}\pi^2}{Dt}+\frac{K_vD}{2t}+\frac{Dt+2D^2}{(t+D)^2}\pi M_s^2\right)\rho_{\mathrm{rms}}, \tag{31}$$

i.e., for the same film thickness, the rougher the surface, the larger the coercivity. This result is quite consistent with the experimental results obtained by, for example, Malyutin *et al.*[2] and Li *et al.*[4]

B. Wall rotation

If a magnetic field H is applied to a thin film and causes the domain to rotate coherently, then the energy of a domain can be expressed as[6,20,21]

$$\begin{aligned}E&=E_w+E_{an}+E_{\mathrm{mag}}+E_H\\&=\sigma_w[1-\cos\varphi]^2+LK_1\sin^2\varphi-\frac{1}{2}LN_eM^2\cos^2\varphi-\frac{1}{2}LN_hM^2\sin^2\varphi-LHM\cos\phi,\end{aligned} \tag{32}$$

where φ is the angle between the magnetization M and the easy axis, and $N_e(N_h)$ is the demagnetizing factor in the easy (hard) direction. ϕ is the angle between the magnetic field H and the magnetization M, $\phi=\theta-\varphi$, where θ is the angle between the magnetic field and the easy axis. At equilibrium $(\partial E/\partial\varphi)=0$, one has

$$\left(K_1+\frac{1}{2}N_eM^2-\frac{1}{2}N_hM^2\right)\sin 2\varphi-2HM\sin(\theta-\varphi)+\frac{\sigma_w}{L}(2\sin\varphi-\sin 2\varphi)=0. \tag{33}$$

Furthermore, $(\partial^2E/\partial\varphi^2)=0$ implies

$$(K_1+N_eM^2-N_hM^2)\cos 2\varphi+HM\cos(\varphi-\theta)+\frac{\sigma_w}{L}(\cos\varphi-\cos 2\varphi)=0. \tag{34}$$

If $\theta=0$, we obtain the coercivity in the easy axis as

$$H_c^{\mathrm{rot}}=\frac{K_1}{M}+(N_e-N_h)M. \tag{35}$$

For the Néel wall, since $N_e=N_h$, H_c^{rot} is independent on surface roughness. However, for the Bloch wall since $N_e=N_{zz}=1-2N_{xx}$, $N_h=N_{xx}$, we have

$$H_c^{\mathrm{rot}}=\frac{K_1}{M}+(1-3N_{xx})M. \tag{36}$$

Clearly, as the roughness increases, the rotational coercivity for the Bloch wall decreases. This conclusion is partially consistent with the experimental result, for example the NiCo film where the coercivity only decreases within a certain roughness regime.[3] The reason can be partly attributed to that the actual domain rotation may not be coherent.[20,21] In fact, the coercivity–roughness relationship for a thick film is

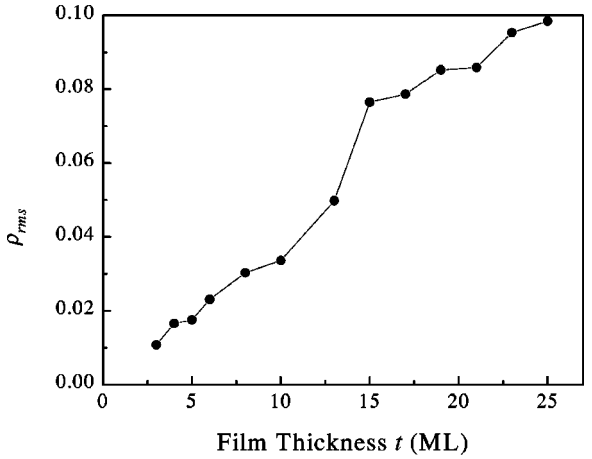

FIG. 3. rms local slope ρ_{rms} as a function of the Co film thickness t for Co/Cu(001) system obtained from Ref. 9. The solid curve is a guide to the eyes.

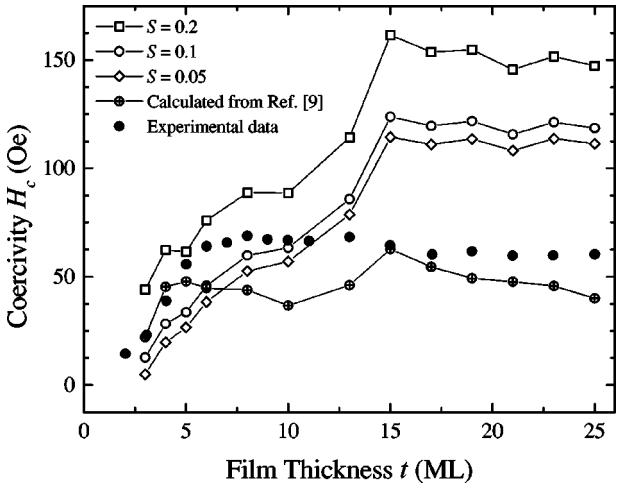

FIG. 4. Coercivity H_c as a function of the Co film thickness t for Co/Cu(001) system. The filled circles are the experimental coercivity obtained from Ref. 9. The $\oplus$ represents the calculated coercivity using the experimental thickness dependent Kerr intensity data in Ref. 9. The open squares, circles, and diamonds are calculated coercivities for average spins 0.2, 0.1, and 0.05, respectively. The solid curves are guides for the eyes.

more complicated than a simple monotonic relationship, and the magnetization reversal process may change with the change of surface roughness.

C. Comparison with experiments

In order to see how the roughness affects the coercivity caused by domain wall movement, we calculate the coercivity of ultrathin Co film grown on Cu(001) using the roughness data from Table I in Ref. 9. Note that during interdiffusion at the Co/Cu interface the Co moment is not quenched in the Cu matrix, but only diluted. Here we assume that the ultrathin Co film has a fcc structure, and that the surface is a self-affine rough surface (this assumption may not be valid; see later discussion). Figure 3 shows the rms slope ρ_{rms} of the Co film as a function of the film thickness t. The rms slope ρ_{rms} increases as t increases. When we calculate the coercivity, we use the following constants for a bulk Co crystal:[19]

$$J = 155\ \mathrm{K}$$

$$a_0 = 2.5\times 10^{-8}\ \mathrm{cm}$$

$$M_s^0 = 1425\ \mathrm{G}$$

$$D = 5\times 10^{-7}\ \mathrm{cm}$$

and the anisotropy constant for a thin Co film:[22]

$$K_v = -2.3\times 10^{6}\ \mathrm{erg/cm^3}$$

$$K_s = 0.034\ \mathrm{erg/cm^3}$$

According to Soohoo,[5] the average spin S for a Co film is less than 0.65 for $t < 100$ Å. However, there is no experimental measurement so far for the S value in the ultrathin film regime. Figure 4 shows the calculated coercivity of the ultrathin Co films as a function of the film thickness t for different average spin S. For various S values, the coercivity increases from 3 to 15 ML, and then gradually decreases from 15 to 25 ML. The overall behavior is qualitatively similar to the experimental data of Jiang *et al.*[9] However, the quantitative values are not exactly the same: the experimental data showed that at $t = 8$ ML the coercivity starts to decrease. There are at least four possible reasons that may contribute to this discrepancy, besides the calculation being for thin films instead of ultrathin films: (1) The absolute thickness of ultrathin Co films could be off by 2–3 ML. The uncertainty comes from the uncertainty in Auger electron escape depth if Auger electron spectroscopy is used. However, the relative monolayer thickness change as observed in HRLEED diffraction peak intensity oscillation in epitaxial layer growth is relatively reliable after the first two layers because the degree of Co and Cu intermixing and the formation of bilayer islands reduce.[9,24,25] More precise thickness determination would require the use of transmission electron microscopy (TEM) imaging.[26] (2) The roughness parameters measured from HRLEED may not be accurate. Comparing Figs. 3 and 4, we can see that the increase of the coercivity value from 11 to 15 ML is due to the increment of the rms local slope from 11 to 15 ML. In fact, the surface morphology of the ultrathin Co film may not be treated as a self-affine surface. Therefore, the method used for a self-affine surface to extract the roughness parameters may not give the true values. Even if the surface is self-affine, the height distribution may not be a Gaussian function. According to Zhao *et al.*,[27] the roughness parameters extracted from the theory of a Gaussian surface are not the same from that extracted from a non-Gaussian surface. (3) According to Soohoo[5] the average spin S is actually a function of the film thickness. However, in our calculation we did not take this thickness dependent S into account. (4) The surface magnetization of Co layer grown on Cu(001) has been observed by magnetization induced second harmonic generation (MSHG) to have one ML period.[28] The Co has a layer-by-layer growth mode and the step density is expected to change periodically with one ML period. The magnetic moments of edge atoms in the two-dimensional islands are not the same as those of nonedge atoms. This contributes to the change in surface mag-

netization. Extensive studies of the ultrathin Co film growth on Cu(100) by various techniques,[9,24,25] show that Co and Cu interdiffusion exists for the first 2–3 ML. For Co film thickness greater than a few monolayers the interdiffusion is suppressed and one can ignore the effect of interdiffusion. A more realistic calculation needs the use of experimentally measured magnetization. Jiang *et al.* measured the relative change of Kerr intensity as a function of Co film thickness,[9] where the Kerr intensity is proportional to magnetization. Since the squareness of measured hysteresis loops (M_R/M_s) is close to one, one can assume that the remnant magnetization is equal to the saturation magnetization. Also we must neglect the third and fourth terms containing exchange constant and in-plane volume anisotropy constant, respectively on the right-hand side of Eq. (29), and rescale the calculated result. Figure 4 plots the calculated coercivity using the experimentally measured relative Kerr intensity versus thickness. We see that the calculated coercivity data are closer to the measured coercivity data.

We should point out that the upper limit of film roughness is the film thickness, i.e., the rms surface roughness amplitude should be smaller than the film thickness. In general, the thickness dependent roughness is strongly related to the film growth modes and the type of material being grown. An example of roughness evolution is depicted in Fig. 3 which shows the local slope ρ_{rms} versus film thickness t. The growth of Co film on Cu(100) surface has a layer by layer growth mode in the first few monolayers.[29]

VI. CONCLUSIONS

We have shown that the roughness of an isotropic self-affine surface changes the demagnetizing factors in magnetic thin films. The roughness induced demagnetizing factors change values differently for Bloch walls and Néel walls. The demagnetizing factor decreases in the direction perpendicular to the film surface in the case of Bloch walls whereas the demagnetizing factor increases in the direction parallel to the film surface in the case of Néel walls. Since the coercivity, magnetic domain wall thickness, and domain sizes are each a function of the demagnetizing factor, one can calculate the change in these magnetic properties as the surface roughness changes. If we neglect anisotropy energy, then the domain wall thickness increases (decreases) as the demagnetizing factor increases for Bloch walls (Néel walls). For a closure domain, the domain size increases (decreases) as the demagnetizing factor increases for Bloch walls (Néel walls). If we replace the local film thickness variation by the rms local slope and assume that the saturation magnetization depends on film thickness, then the calculated coercivity from domain wall movement for a fcc film increases as the local slope increases. We found the calculated coercivity versus thickness is in qualitative agreement with experimental data of Co ultrathin films grown on Cu(001) surfaces. For the same film thickness, the coercivity of thin magnetic films increases with surface roughness, which is qualitatively consistent with many experimental results. We also find the coercivity for coherent domain rotation for the Bloch wall decreases as the roughness increases.

ACKNOWLEDGMENTS

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